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Lecture 2: Hyperon Production and Spin Dynamics

PANDA lecture week, December 11-15, 2017

Karin Schönning, Uppsala University

Outline

- Summary of lecture 1
- Spin observables in $\bar{p}p \to \bar{Y}Y$
  - Sequential hyperon decays
  - The spin $\frac{3}{2}$ case
- CP violation in hyperon decays
- Questions for discussion

Summary of lecture 1

- Hyperons serve as a diagnostic tool for questions like
  – Why and how quarks are bound into hadrons?
  – How is mass generated by the strong interaction?
  – Matter-antimatter asymmetry of the Universe?

- Degrees of freedom unclear in processes involving strange hyperons.
- Spin observables powerful tool in testing models.
- Strong and EM production allows polarisation perpendicular to the production plane.
- Polarisation extracted from decay angular distributions.

Spin observables in $\bar{p}p \to \bar{Y}Y$

The angular distribution is obtained by the trace

$$I_0^{\bar{B}B} = \mathrm{Tr}(\rho^{\bar{B}B})$$

With an unpolarised beam and unpolarised taget this becomes

$$I_{\bar{B}B}(\Theta_{\bar{Y}},\hat{\bar{k}},\hat{k}) = \frac{I_0}{64\pi^3}\left(\begin{array}{l} 1 \\ +P_{\bar{Y},y}\bar{\alpha}\bar{k}_y + P_{Y,y}\alpha k_y \\ +C_{xx}\bar{\alpha}\alpha\bar{k}_x k_x \\ +C_{yy}\bar{\alpha}\alpha\bar{k}_y k_y \\ +C_{zz}\bar{\alpha}\alpha\bar{k}_z k_z \\ +C_{xz}\bar{\alpha}\alpha\bar{k}_x k_z \\ +C_{zx}\bar{\alpha}\alpha\bar{k}_z k_x \quad . \end{array}\right)$$

Polarisation and **spin correlations:**
- Production related.
-Depend on energy and scattering angle.
- Independet of decay.

Spin observables in $\bar{p}p \to \bar{Y}Y$

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Asymmetry:
- Decay related.
- Independent on energy and scattering angle.
- Depend on decay.

Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

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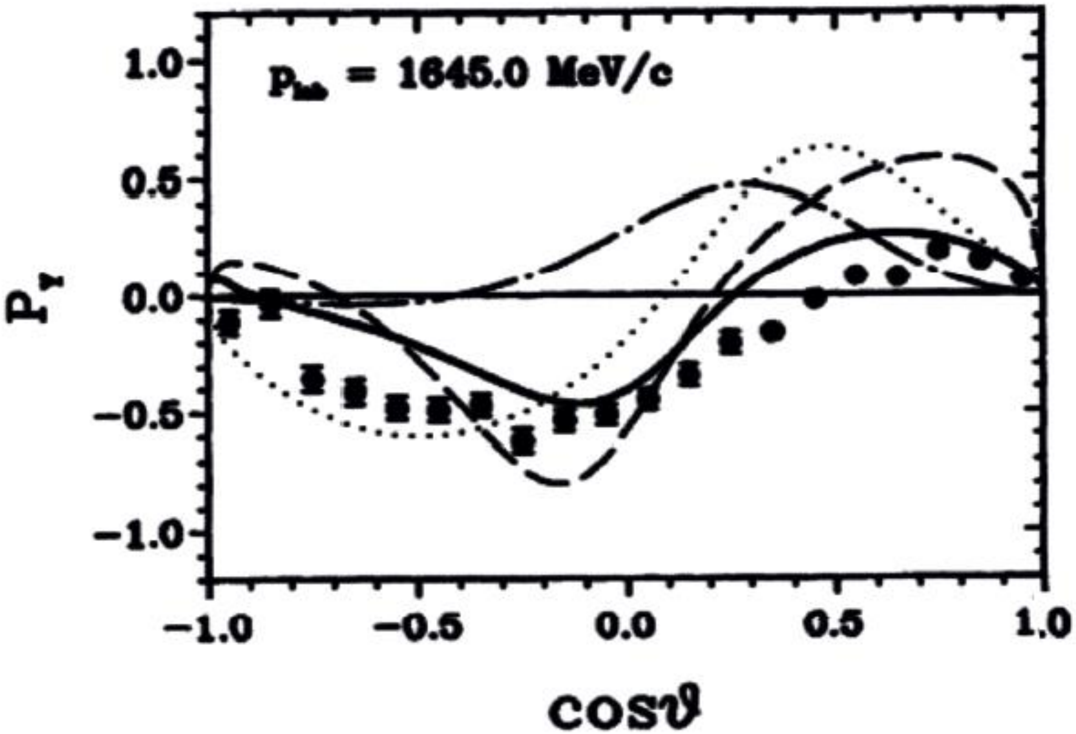
Angles/four vectors: measured in the experiment.

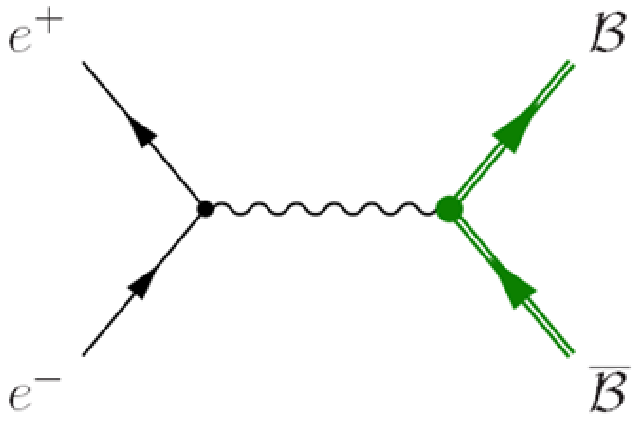
Hyperons from $\bar{p}p$ reactions

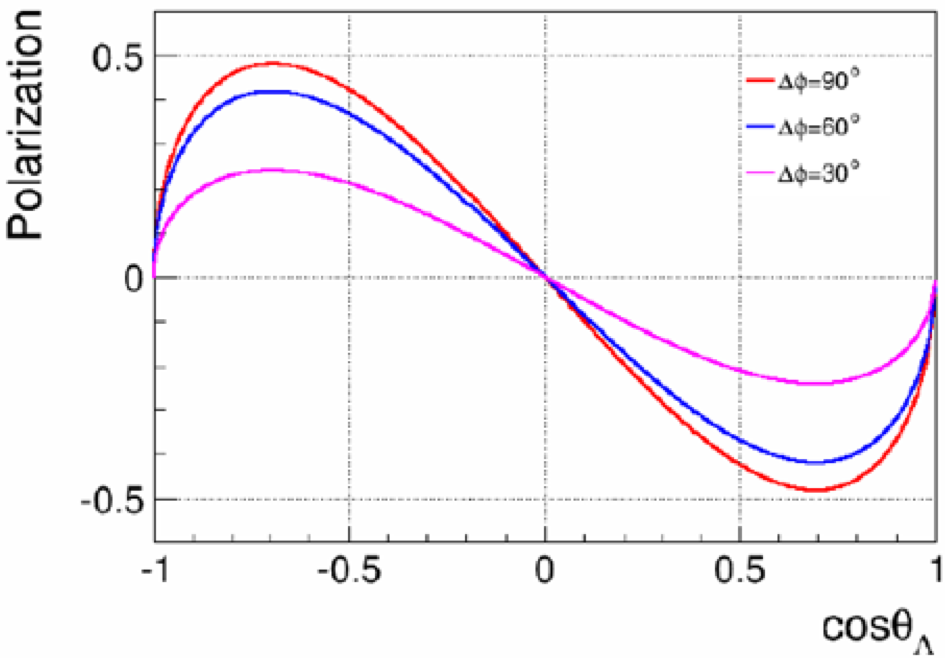


The polarisation depend on energy and angle, and different models predict different dependencies.

Figure from Phys. Rep. 368 (2002) 119.

The EMFF phase and polarization



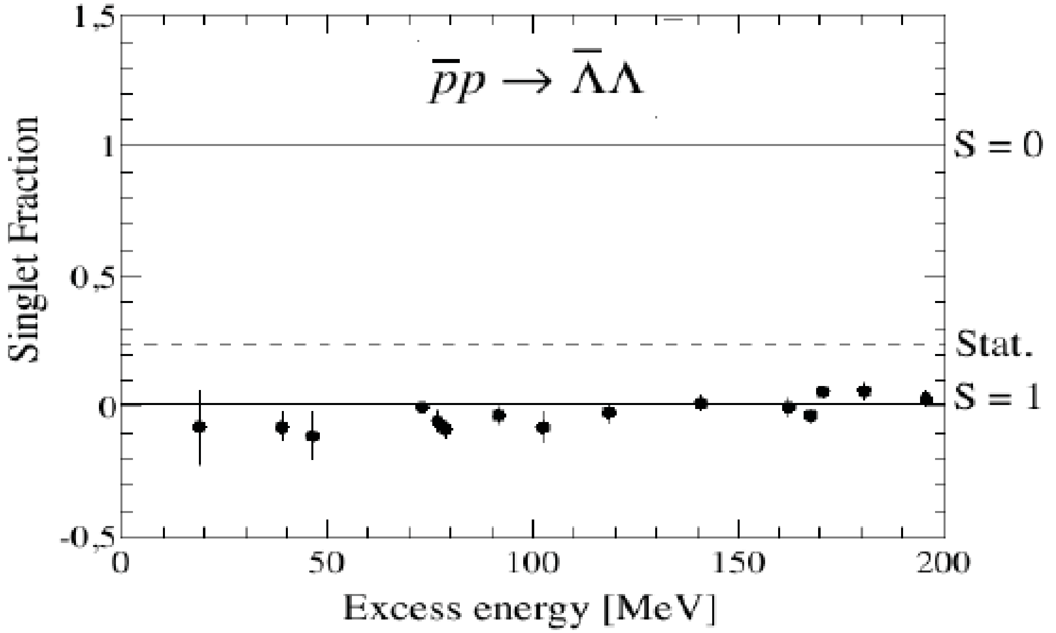


This is very different from the $e^+e^- \to \bar{Y}Y$ where the angular dependence can be parameterised in terms of electromagnetic form factors (EMFF's)*

$$P_n = -\frac{\sin 2\theta Im[G_E(Q^2)G_M^*(Q^2)]/\sqrt{\tau}}{(|G_E(Q^2)|^2 \sin^2\theta)/\tau + |G_M(Q^2)|^2(1+\cos^2\theta)}$$

*Nuovo Cim. A 109 (1996) 241.
** hep-ph 1702.07288

Spin observables in $\bar{p}p \to \bar{Y}Y$



- The *singlet fraction* can be defined as

$$SF = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

- The PS185 experiment found that $\bar{\Lambda}\Lambda$ are almost exclusively produced in a spin triplet state*.

*PRC 54 (1996) 1877

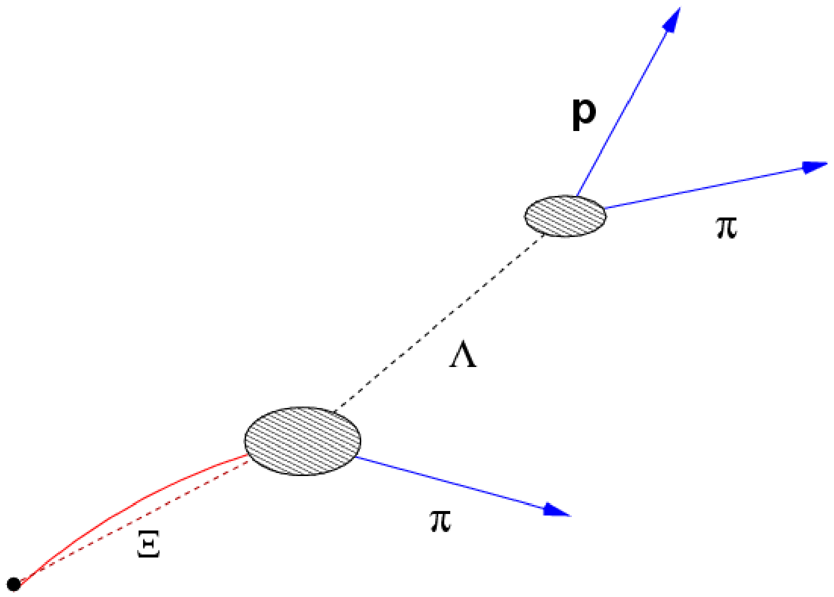
Subsequent hyperon decays

Consider a hyperon decaying into another hyperon, *e.g.* $\Xi \rightarrow \Lambda\pi$.

Spinwise this can be described as

$$\frac{1}{2} \rightarrow \frac{1}{2}\, 0 \rightarrow \frac{1}{2}\, 0\ 0$$

In this case we have two decay matrices, denoted T_1 and T_2.



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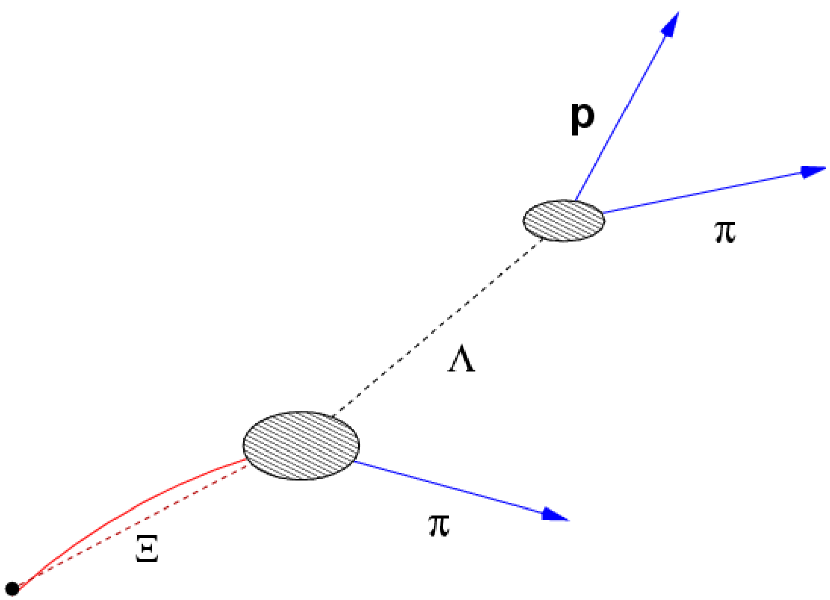


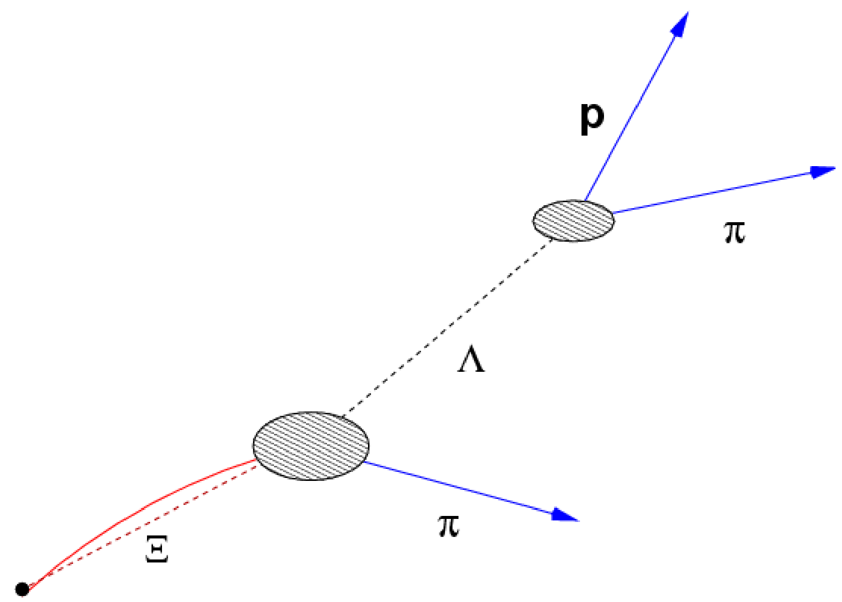
The joint angular distribution is given by

$I = Tr(T_2 T_1 \rho T_1^{\intercal} T_2^{\intercal})$

Spin observables for spin $\frac{1}{2}$ hyperons

By calculating the trace $Tr(T_2 T_1 \rho T_1^\dagger T_2^\dagger)$
and integrating over the intermediate hyperon angles, the proton angular distribution is given by

$$I(\theta_{\mathrm{p}}, \phi_{\mathrm{p}}) = \frac{1}{4\pi}\left(1 + \alpha_{\Xi}\alpha_{\Lambda}\cos\theta_{\mathrm{p}} + \frac{1}{2}\alpha_{\Lambda}P_y \sin\theta_{\mathrm{p}}(\beta_{\Xi}\cos\phi_{\mathrm{p}} + \gamma_{\Xi}\sin\phi_{\mathrm{p}})\right)$$



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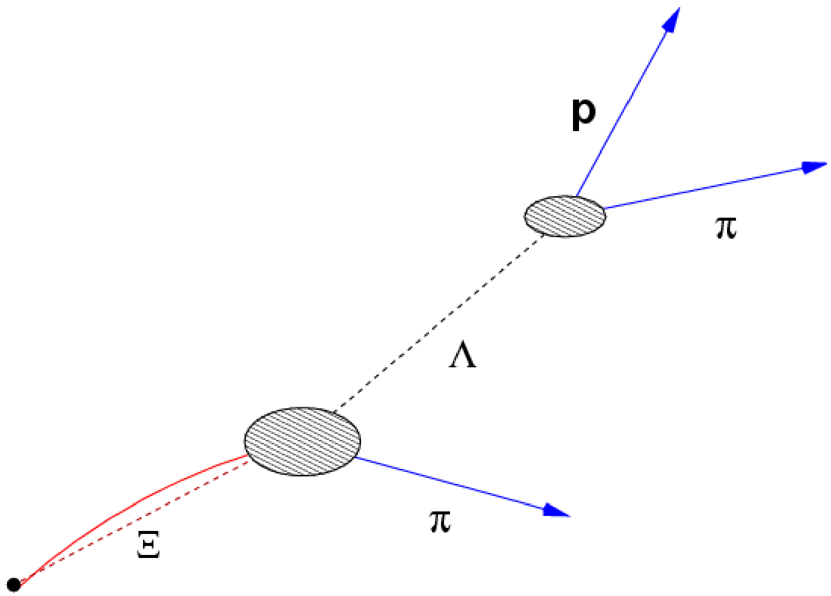
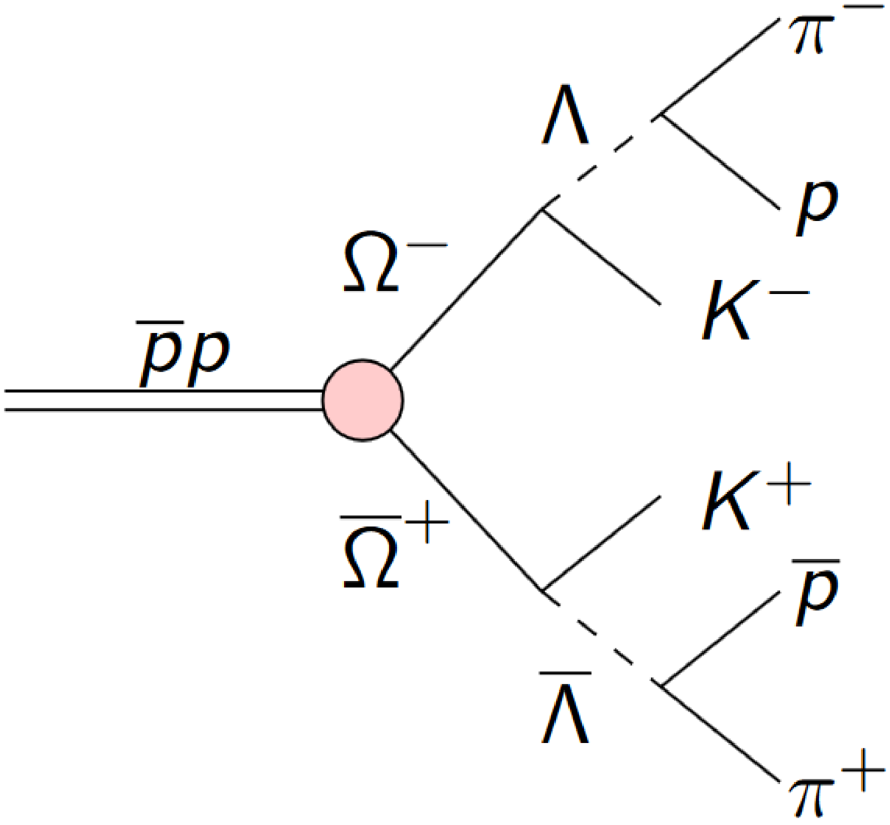


In this way one can extract β and γ !

Spin observables for spin $\frac{3}{2}$ hyperons



Spin observables for spin $\frac{3}{2}$ hyperons

The Ω hyperon is more complicated.

- Spin $\frac{1}{2}$: **3** polarisation parameters: $\boldsymbol{r_{-1}^{1}}$, $\boldsymbol{r_{0}^{1}}$ and $\boldsymbol{r_{1}^{1}}$ (P_X, P_Y and P_z)
- Spin $\frac{3}{2}$: **15** polarisation parameters: $\boldsymbol{r_{-1}^{1}}$, $\boldsymbol{r_{0}^{1}}$, $\boldsymbol{r_{1}^{1}}$, $\boldsymbol{r_{-2}^{2}}$, $\boldsymbol{r_{-1}^{2}}$, $\boldsymbol{r_{0}^{2}}$, $\boldsymbol{r_{1}^{2}}$, $\boldsymbol{r_{2}^{2}}$, $\boldsymbol{r_{-3}^{3}}$, $\boldsymbol{r_{-2}^{3}}$, $\boldsymbol{r_{-1}^{3}}$, $\boldsymbol{r_{0}^{3}}$, $\boldsymbol{r_{1}^{3}}$, $\boldsymbol{r_{2}^{3}}$ and $\boldsymbol{r_{3}^{3}}$.

Spin observables for spin $\frac{3}{2}$ hyperons

Density matrix:

- Spin $\frac{3}{2}$: **15** polarisation parameters: $\boldsymbol{r_{-1}^{1}, r_{0}^{1}, r_{1}^{1}, r_{-2}^{2}, r_{-1}^{2}, r_{0}^{2}, r_{1}^{2}, r_{2}^{2}, r_{-3}^{3}, r_{-2}^{3}, r_{-1}^{3}, r_{0}^{3}, r_{1}^{3}, r_{2}^{3}}$ and $\boldsymbol{r_{3}^{3}}$.
- Strong production process → parity is conserved → **8** polarisation parameters equal 0.
- Resulting density matrix $\rho\left(\frac{3}{2}\right)$:*

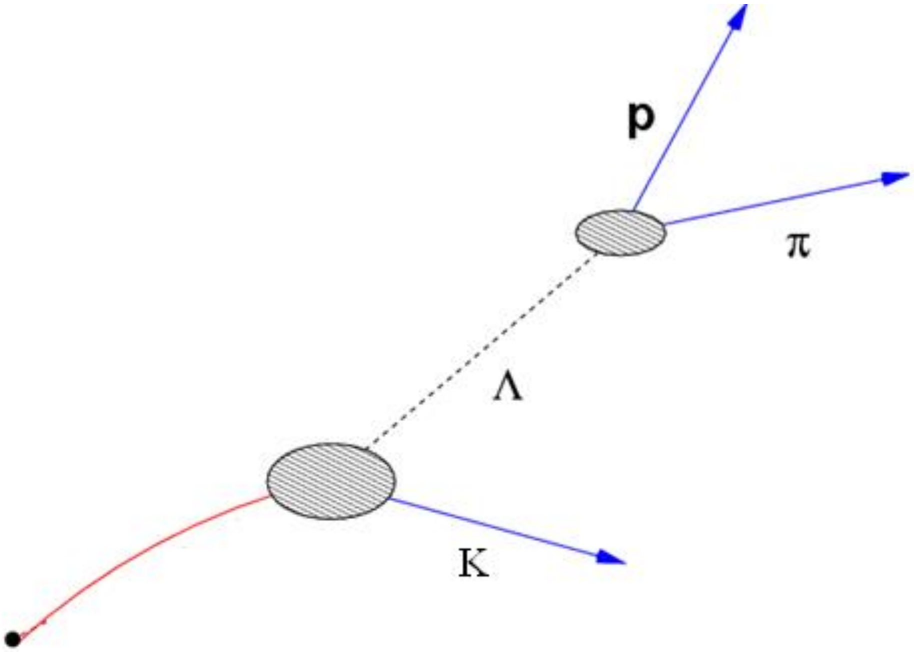
$$\frac{1}{4}\begin{bmatrix} 1+\sqrt{3}r^2_0 & -i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r^2_1-i\sqrt{\frac{6}{5}}r^3_{-1} & \sqrt{3}r^2_2-i\sqrt{3}r^3_{-2} & -i\sqrt{6}r^3_{-3} \\ i\sqrt{\frac{6}{5}}r^3_{-1}+i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r^2_1 & 1-\sqrt{3}r^2_0 & -i2\sqrt{\frac{3}{5}}r^1_{-1}+i3\sqrt{\frac{2}{5}}r^3_{-1} & \sqrt{3}r^2_2+i\sqrt{3}r^3_{-2} \\ \sqrt{3}r^2_2+i\sqrt{3}r^3_{-2} & i2\sqrt{\frac{3}{5}}r^1_{-1}-i3\sqrt{\frac{2}{5}}r^3_{-1} & 1-\sqrt{3}r^2_0 & -i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r^2_1-i\sqrt{\frac{6}{5}}r^3_{-1} \\ i\sqrt{6}r^3_{-3} & \sqrt{3}r^2_2-i\sqrt{3}r^3_{-2} & i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r^2_1+i\sqrt{\frac{6}{5}}r^3_{-1} & 1+\sqrt{3}r^2_0 \end{bmatrix}$$

* Erik Thomé, PhD thesis, Uppsala University (2012)

Spin observables for spin $\frac{3}{2}$ hyperons

Consider the decay $\Omega^- \to \Lambda K^- \to p\pi^- K^-$.

Spinwise this is $\frac{3}{2} \to \frac{1}{2}\, 0 \to \frac{1}{2}\, 0\ 0$.

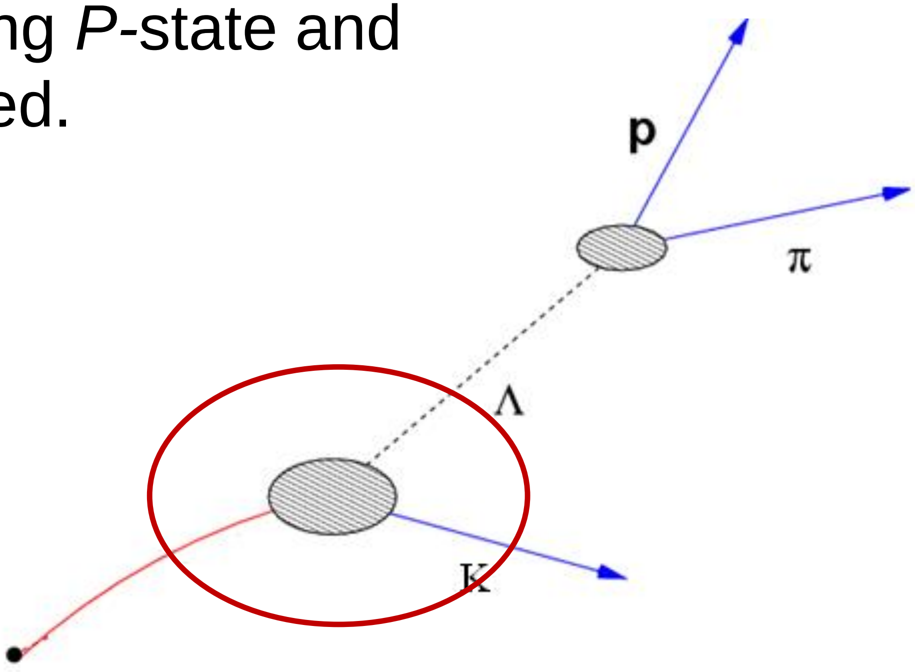


Spin observables for spin $\frac{3}{2}$ hyperons

First, let's focus on $\Omega^- \to \Lambda K^-$, *i.e.* $\frac{3}{2} \to \frac{1}{2}\,0$.

Weak decay: parity conserving *P*-state and parity violating *D*-state allowed.

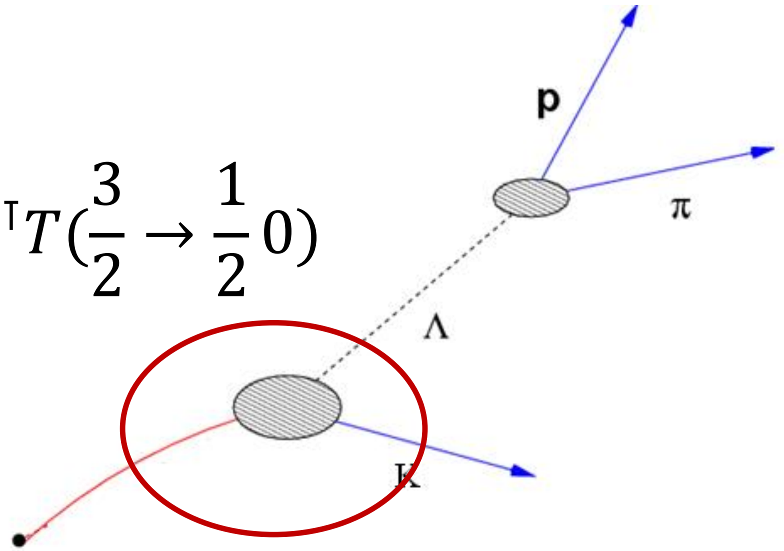
Amplitudes: T_P and T_D.



Spin observables for spin $\frac{3}{2}$ hyperons

Angular distribution given by

$$I(\theta,\varphi) = Tr(\rho(\frac{3}{2})T^{\dagger}T(\frac{3}{2}\rightarrow\frac{1}{2}0)$$



$$\begin{aligned}I(\theta,\phi) &= \mathrm{Tr}(\rho(3/2)T^{\dagger}T(3/2\rightarrow 1/2\,0))\\ &= \frac{1}{4\pi}\Big[1+\frac{\sqrt{3}}{2}(1-3\cos^2\theta)r_0^2-\frac{3}{2}\sin^2\theta\cos 2\phi\, r_2^2-\frac{3}{2}\sin 2\theta\cos\phi\, r_1^2\\ &+\frac{1}{40}\alpha\sin\theta\Big(8\sqrt{15}r_{-1}^1\sin\phi-9\sqrt{10}r_{-1}^3(3+5\cos 2\theta)\sin\phi\\ &-30(3r_{-2}^3\sin 2\phi\sin 2\theta+\sqrt{6}r_{-3}^3\sin 3\phi\sin^2\theta)\Big)\Big]\end{aligned}$$

*Elisabetta Perotti, FAIRNESS (2017)

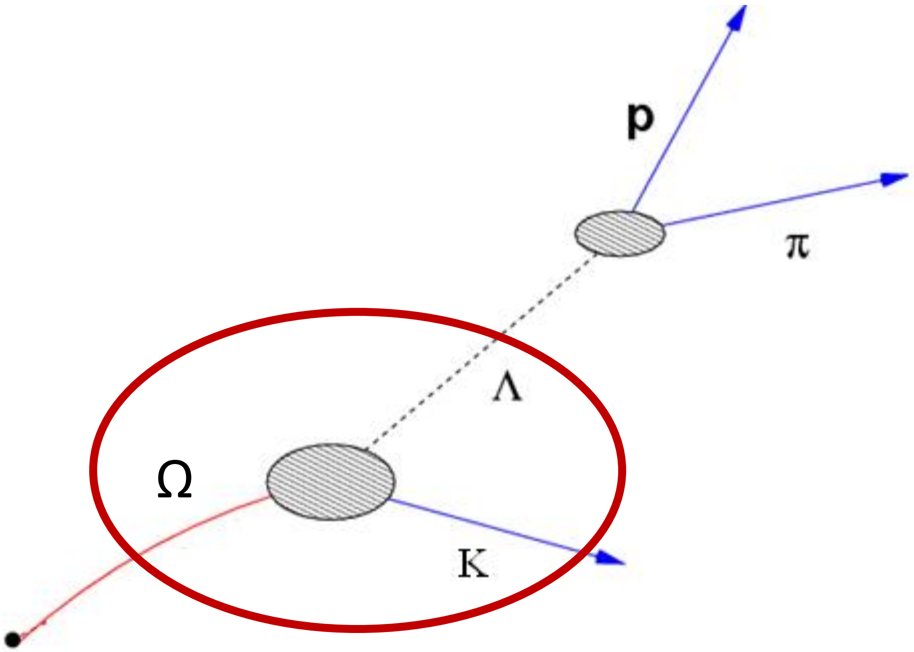
Spin observables for spin $\frac{3}{2}$ hyperons

Using the *method of moments,* the **3** polarisation parameters $\boldsymbol{r_2^2}$, $\boldsymbol{r_1^2}$, $\boldsymbol{r_0^2}$ can be extracted from the angular distribution of the Λ:*

$$< sin\theta_\Lambda > = \frac{\pi}{32}(8 + \boldsymbol{r_0^2}\sqrt{3})$$

$$< cos\varphi_\Lambda cos\theta_\Lambda > = -\frac{3\pi}{32}\boldsymbol{r_1^2}$$

$$< sin^2\varphi_\Lambda > = \frac{1}{4}(2 + \boldsymbol{r_2^2})$$

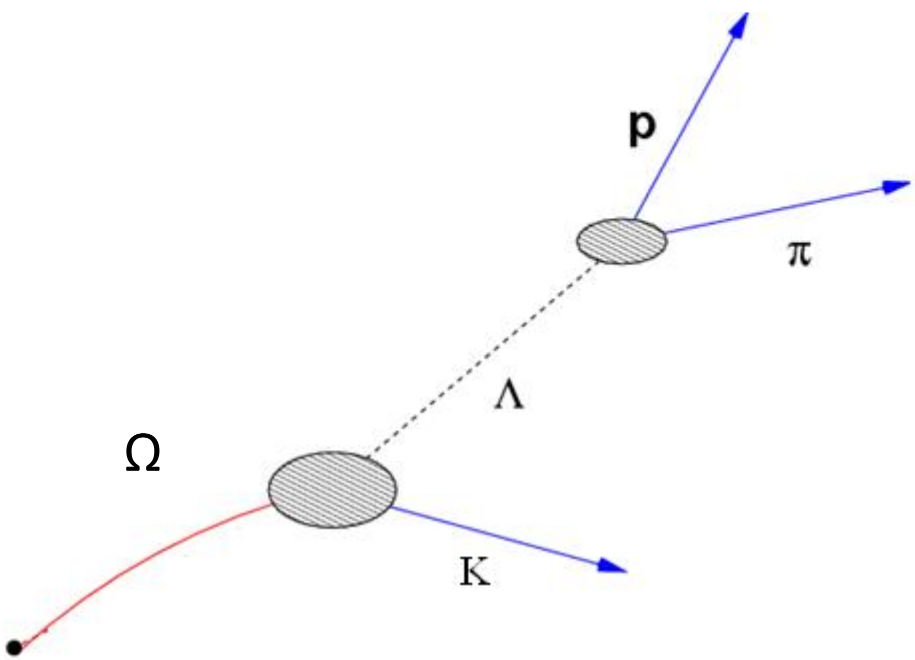


*Elisabetta Perotti, FAIRNESS (2017)

Spin observables for spin $\frac{3}{2}$ hyperons

$$\langle \sin\phi_\Lambda \cos\phi_\mathrm{p}\rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\Lambda \cos\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= -\frac{3\pi^2 \alpha_\Lambda \gamma_\Omega r^3_{-2}}{1024}$$
$$\langle (3\cos\theta_\Lambda - 1)\sin\phi_\mathrm{p}\rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times (3\cos\theta_\Lambda - 1)\sin\phi_\mathrm{p} d\Omega_\Lambda d$$
$$= -\frac{\pi \alpha_\Lambda \gamma_\Omega r^3_{-1}}{4\sqrt{10}}$$
$$\langle \sin\phi_\mathrm{p}\rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{160}\left(-4\sqrt{15} r^1_{-1} + \sqrt{10} r^3_{-1}\right)$$
$$\langle \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_\mathrm{p}\rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{640}\left(5\sqrt{6} r^3_{-3} + 4\sqrt{15} r^1_{-1} - \sqrt{10} r^3_{-1}\right)$$

Four polarisation parameters can be determined from the joint angular distributions of the Λ and the proton *:



*Erik Thomé, Ph. D. Thesis and Elisabetta Perotti, FAIRNESS

Spin observables for spin $\frac{3}{2}$ hyperons

$$\langle \sin\phi_\Lambda \cos\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\Lambda \cos\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= -\frac{3\pi^2 \alpha_\Lambda \gamma_\Omega r^3_{-2}}{1024}$$

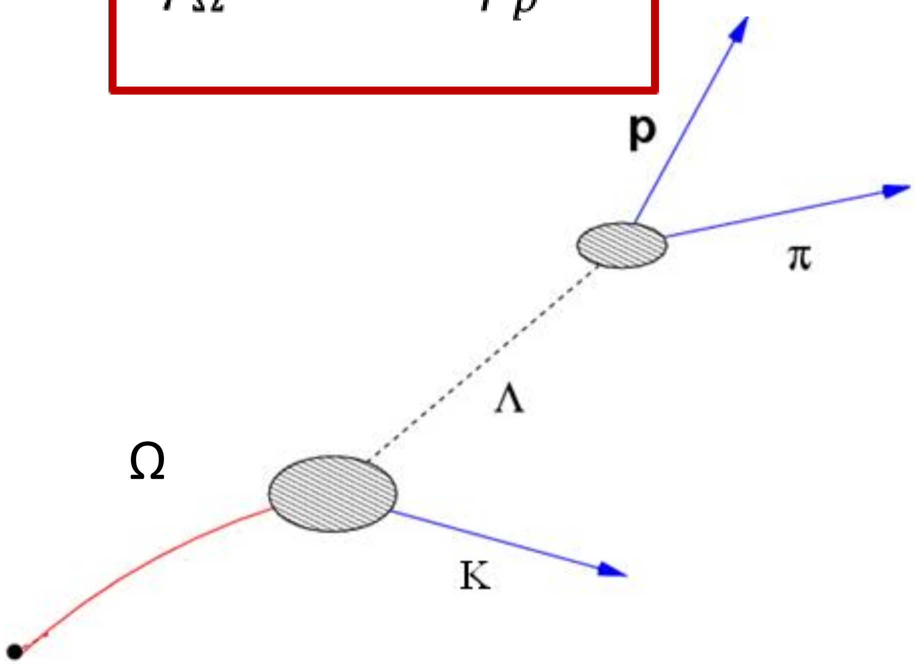
$$\langle (3\cos\theta_\Lambda - 1) \sin\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times (3\cos\theta_\Lambda - 1) \sin\phi_\mathrm{p} d\Omega_\Lambda$$
$$= -\frac{\pi \alpha_\Lambda \gamma_\Omega r^3_{-1}}{4\sqrt{10}}$$

$$\langle \sin\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{160} \left(-4\sqrt{15} r^1_{-1} + \sqrt{10} r^3_{-1} \right)$$

$$\langle \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{640} \left(5\sqrt{6} r^3_{-3} + 4\sqrt{15} r^1_{-1} - \sqrt{10} r^3_{-1} \right)$$

Furthermore:

$$\frac{\beta_\Omega}{\gamma_\Omega} = \frac{< cos\varphi_p >}{< sin\varphi_p >}$$



*Erik Thomé, Ph. D. Thesis and Elisabetta Perotti, private communication

Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

- Spin $\frac{1}{2}$ hyperons (Λ, Ξ, Λ_c) :
  - Polarisation.
  - Spin correlations and singlet fraction:

$$SF = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

- Spin $\frac{3}{2}$ hyperons into spin $\frac{1}{2}$ hyperons ($\Omega \rightarrow \Lambda K$):
  - 7 polarisation parameters + degree of polarisation.

$$d(\rho) = \sqrt{\sum_{L=1}^{2j} \sum_{M=-L}^{L} (r_M^L)^2}$$

CP violation in hyperon decays

CP violation in hyperon decays

More matter than anti-matter in the Universe –why?

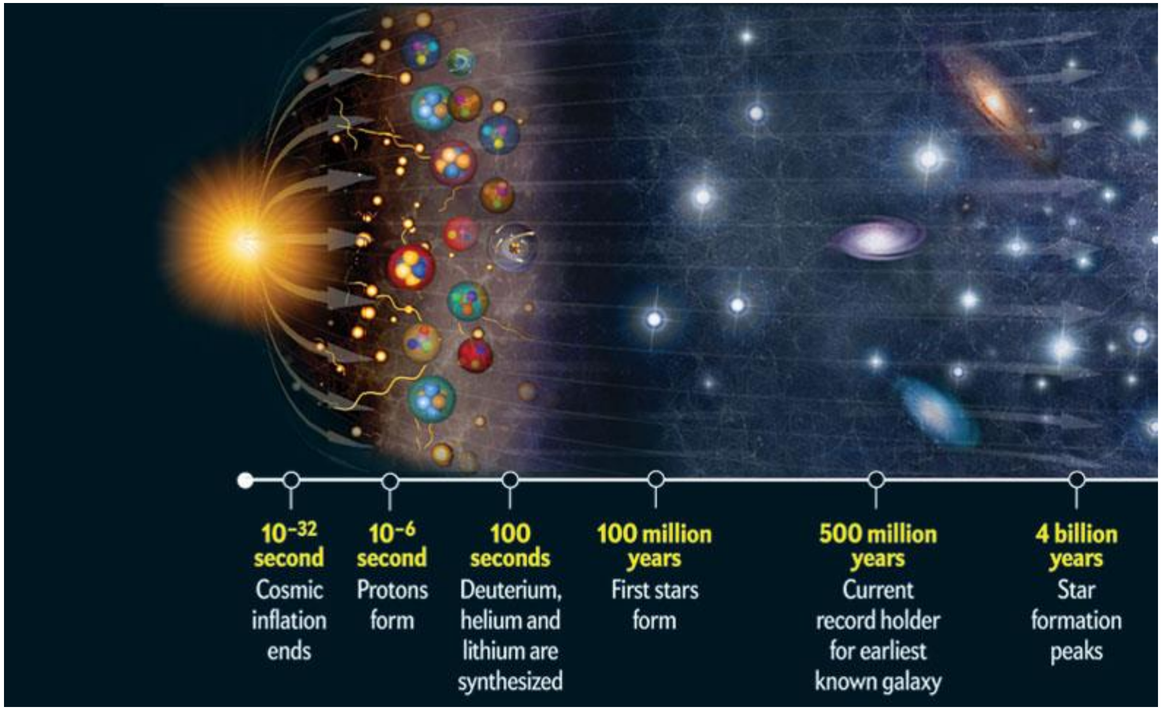
- As much matter/baryons as anti-matter/anti-baryons, should have been created in the Big Bang.
- Where did the anti-baryons go
 (*”Baryogenesis”)?*

Picture from Virginia Tech

CP violation in hyperon decays

The Sakharov criteria:

- There must be processes that do not conserve baryon number.
- There must be processes that violate CP-symmetry
- These processes must have occurred outside thermal equilibrium



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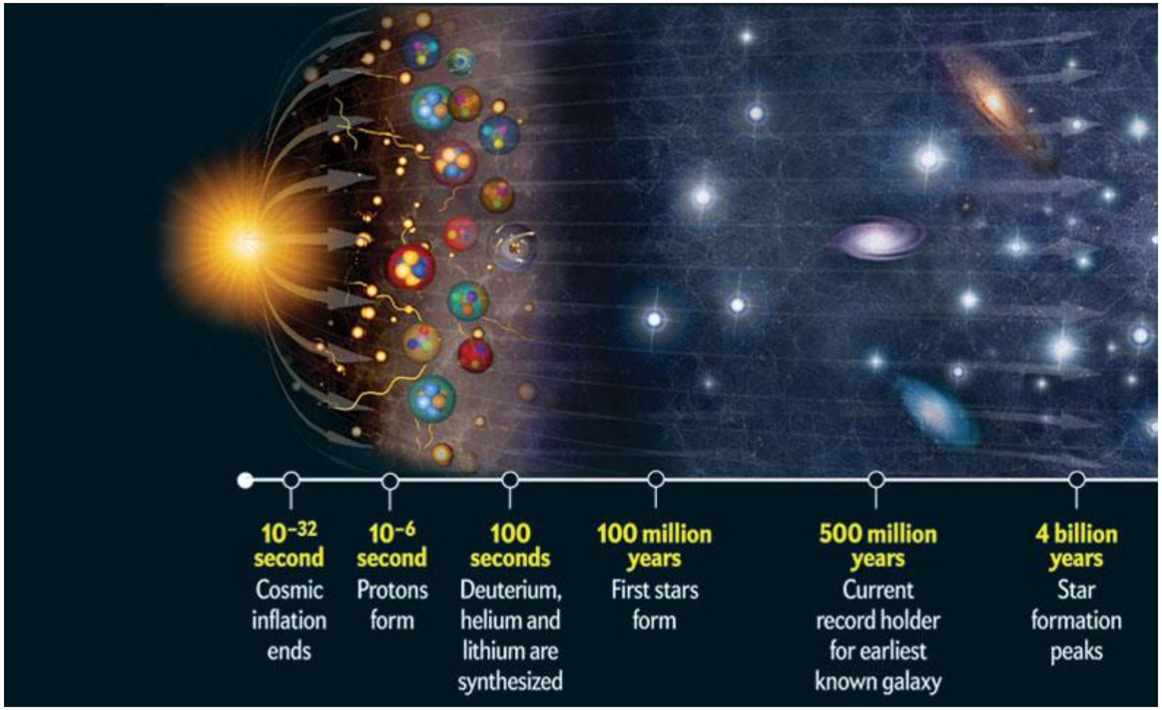
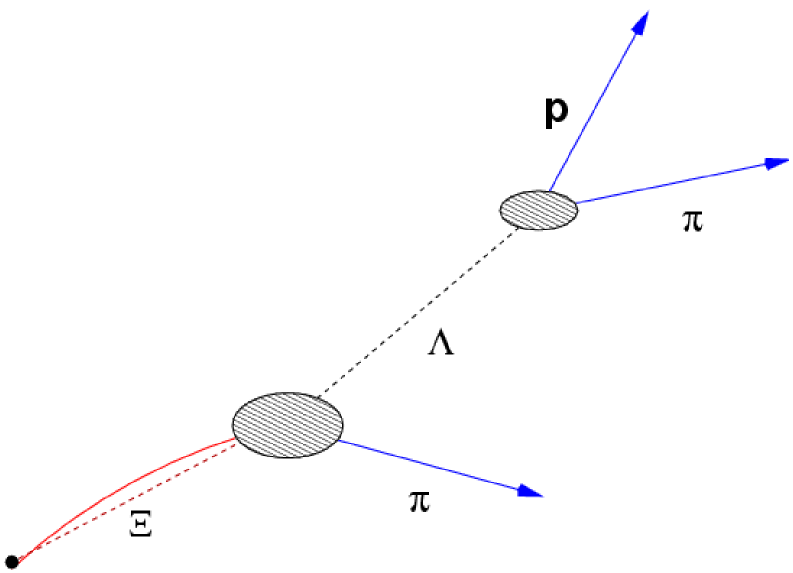


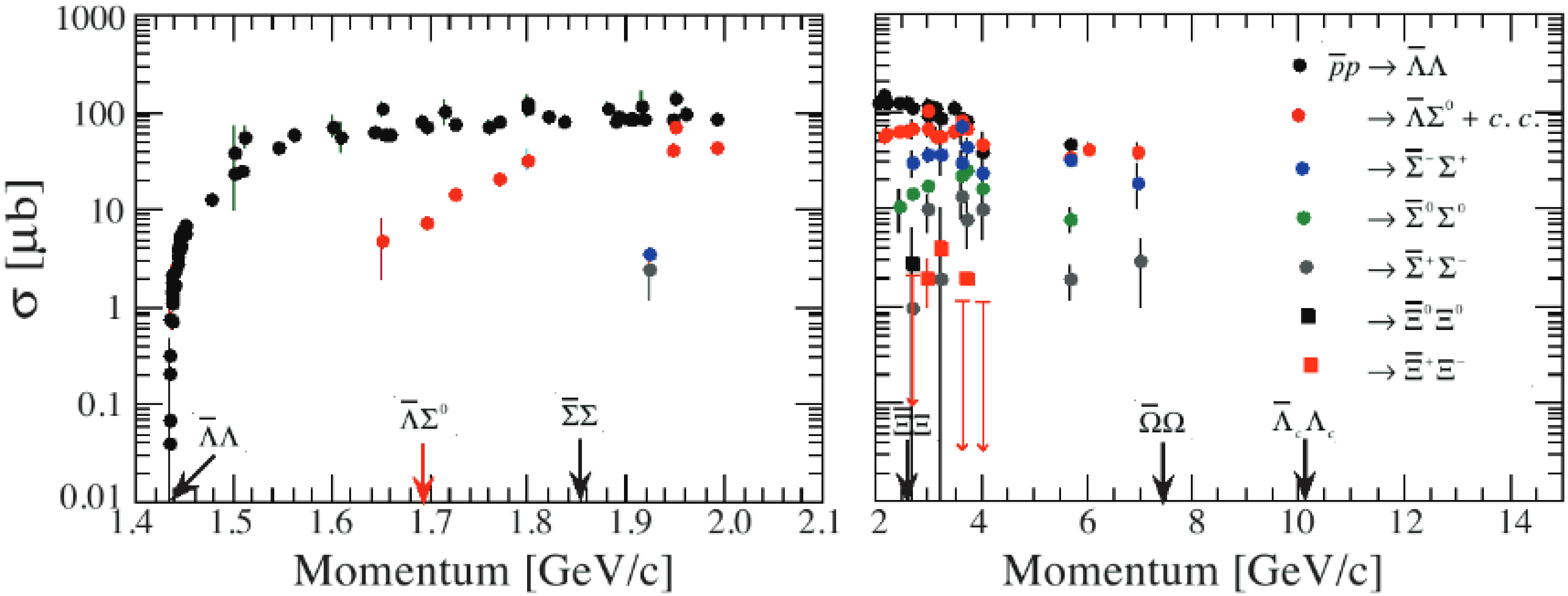
CP violation in hyperon decays

- Standard Model CP violation too small to explain asymmetry
- CP violation beyond SM never observed for baryons (LHCb observation within SM)
- The $\bar{p}p \to \bar{Y}Y$ process suitable for CP measurements (clean, no mixing)
- If CP valid, $\alpha = -\bar{\alpha}$ and $\beta = -\bar{\beta}$
- CP violation quantified by *e.g.*:

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$



Previous measurements of $\bar{p}p \to \bar{Y}Y$



- A lot of data on $\bar{p}p \longrightarrow \bar{\Lambda}\Lambda$ near threshold, mainly from PS185 at LEAR*.
- Very scarce data bank above 4 GeV.
- Only a few bubble chamber events on $\bar{p}p \longrightarrow \bar{\Xi}\Xi$
- No data on $\bar{p}p \longrightarrow \bar{\Omega}\Omega$ nor $\bar{p}p \longrightarrow \bar{\Lambda}_c\Lambda_c$

* See *e.g.* T. Johansson, AIP Conf. Proc. Of LEAP 2003, p. 95.

Time-line, hyperon physics with PANDA

- PANDA physics from **Day One**:
  - Single- and double strange hyperon spectroscopy.
  - Spin observables of single- and double strange hyperons.
- **First years** of PANDA:
  - Triple strange hyperon spectroscopy.
  - Polarisation parameters of Ω^-.
- **Long-term** projects with high luminosity:
  - Single charm baryon spectroscopy.
  - Spin observables of Λ^+_c.
  - CP violation in Λ and Ξ decays.

Questions for discussion

- Which decay asymmetry parameters of Λ, Ξ and Ω are known? Check the PDG and see what there is left to do!
- Why would PANDA be a good experiment for testing CP symmetry in hyperon decays?
- What are the main challenges for testing CP symmetry with PANDA?

Thanks to:

Stefan Leupold, Elisabetta Perotti, Tord Johansson, Erik Thomé and Walter Ikegami-Andersson.

Backup

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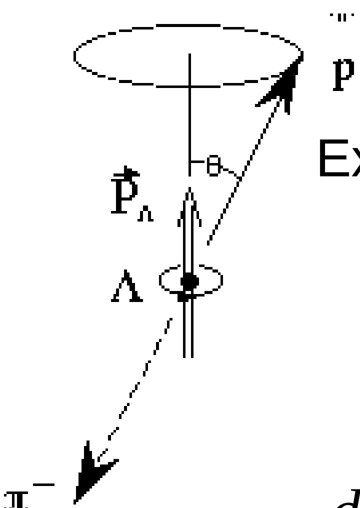
Spin observables for spin $\frac{1}{2}$ hyperons

Method of Moments

The expectation value or the moment of a function *g(x)* can be written

$$\langle g(x)\rangle = \int_{\Omega} g(x)\, f(x\,|\,\theta)\,dx$$



where *f(x|θ)* is a probability density function.

Example: Λ hyperon with polarisation P_n decaying into $p\ \pi^-$. Then

$$f(\theta_p\,|\,P_n) = \frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda P_n \cos\theta_p$$

and thus

$$\langle\cos\theta_p\rangle = \int \frac{dN}{d\cos\theta_p}\cos\theta_p\, d\cos\theta_p = \int (1+\alpha_\Lambda P_n\cos\theta_p)\cos\theta_p\, d\cos\theta_p = \frac{\alpha_\Lambda P_n}{3}$$

which means that the polarisation can be expressed as $P_n = \dfrac{3}{\alpha_\Lambda}\langle\cos\theta_p\rangle$